

# Variable Speed Generators with High Fuel Savings

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## 3.6 Variable Speed Generators with High Fuel Savings

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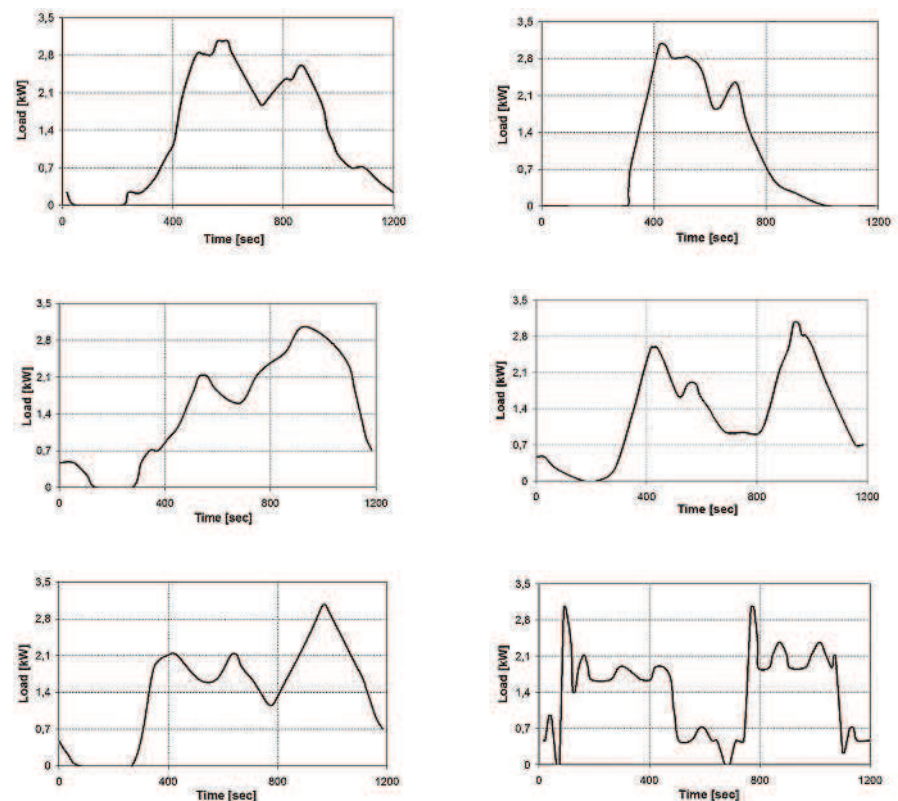
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### Abstract

Auxiliary power units (APUs) are used in mobile applications to supply electrical power in the range of 3 to 10 kW. The state of the art generators are driven by a diesel engine at constant speed. They have a low efficiency (high fuel consumption) as they operate mostly in partial load conditions. A higher efficiency for partial loads is feasible by adjusting the speed of the diesel engine to its optimum efficiency. A frequency converter provides a constant electric frequency at variable speed of the generator. The resulting higher investments for such a variable speed generator (VSG) need a proof of economics, which is demonstrated by this investigation.

### Introduction

Small diesel electric generators are used in mobile applications to provide power for auxiliary electric appliances (air conditioning, micro-wave oven, lightning,



**Table 1:** Considered representative duty cycles

TV, etc.) during off-driving time periods to suit the need of the driver. The APUs allow to stop the big main diesel drive, as its fuel consumption in idle mode for battery charging is high due to its internal friction. Fields of application are military applications, ambulances, police

vehicles, camper vans and long-haul trucks. Especially long-haul trucks are of interest due to its high market potential particularly in the US [1]. The state of the art APU systems are based on basic constant speed generators.

However, such a diesel-electric APU has a low efficiency at partial loads.

An electronic converter (inverter) allows to design a VSG with a constant electric frequency output. These devices are proven for other purposes, e.g. hybrid systems [3]. But an APU with a VSG technology is still not established as its higher investment is not yet proven to be economical. The fuel consumption is analysed in this paper for several typical load profiles using a VSG – thus proving the economics.

### Duty cycles and control strategies

Long distance truck drivers keep their main diesel engine running after driving (if no APU is installed) to supply the cabin with power for auxiliaries, especially in the US. The engine is, therefore, kept idling overnight and generates high air pollution. This led the Californian government to ban idling of trucks over 10,000 pounds (4,5 t) for more than 5 min [4]. Duty cycles for this application ([5], [6]) are considered in this project. German load cycles were selected for other applications. The German Association VDEW (today BDEW) generated a variety of different duty cycles. These VDEW-profiles are based on measured values and represent an approximation of the real demand [7]. The following profiles have been chosen:

- The load profile “Domestic” represents the demand of a household. It is relevant for yachts, caravans, recreational vehicles and long-haul trucks.
- Three load cycles cover professional applications as law enforcement, rescue or specialty vehicles. The first one describes the demand of businesses in general, the second one the power demand of businesses weekdays from 8 a.m. to 6 p.m. and the third one shows businesses with highest demand in the evening.
- A fourth one represents the power demand for a remote farm.

Four different control strategies were chosen for the comparative tests:

1. Constant speed of revolution
2. Constant speed with start/stop-function
3. Variable speeds of revolution
4. Variable speeds with start/stop-function

The constant speed mode represents a standard generator. As the profiles were scaled to the peak power, this system needed to be run at maximum engine speed at 3600 rpm. The start/stop-function switches off the engine when no power is needed. A speed range of 1500-3600 rpm was chosen for the variable speed mode.

### Simulation

A simulation model was created to analyse two different issues:

1. To calculate the fuel consumption of the engine for the given profiles.
2. To determine the optimum efficiency of the system for different load cases.

The first one is used for verification of the model. Comparing the simulation results with the test results quickly identifies errors in measurements or simulations. It is also used to proof fuel consumption reduction of other load profiles to determine the rotary speeds of the diesel for highest system efficiencies. The objective was to interpolate these points and to provide a characteristic curve of the system which was stored in the control device of the diesel engine. Thus, the system operated at best efficiencies for any power demand. Figure 3.6-1 represents the test set up. For the simulations, only the drivetrain with diesel engine, generator and inverter, was examined.

In contrast to real APU systems, a buffer battery was not part of the system. A battery is indispensable if spontaneous load peaks occur and the engine operates in a low rotary speed. The focus was on the reduction of fuel consumption of the

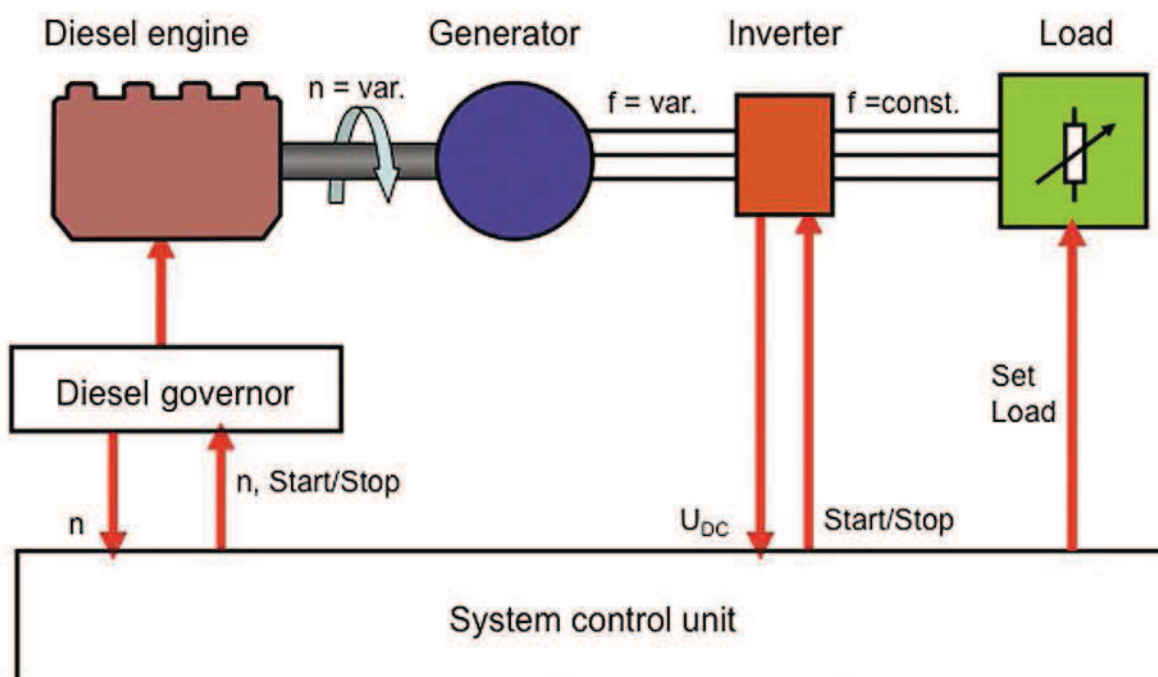


Fig. 3.6-1: Set up of the analysed system

system, so that the profile was “known” by the control unit and a battery was not needed.

The characteristics of the components were needed for the simulation. The characteristic map of the diesel engine was provided by the Company Hatz. The maps of the inverter and the generator were measured on the test bench, Figure 3.6-2. The simulation model was designed by Matlab®. An algorithm was programmed which calculates the points of best efficiency for each (electric) power demand. This resulted in the curve of optimum efficiency of Figure 3.6-3. The lines of constant electric power are deformed due to the efficiencies of inverter and generator. The area of highest system efficiency is at the top of the characteristic diesel engine field and located at the curve of maximum engine torque. This resulting curve was used for the control unit which adapts the rotary speed of the diesel engine to the present load.

#### Test bench and results

The control let the diesel engine time to change its speed when the power increased as there is no energy buffer. The system control unit had the following tasks:

- Control of the load: The control unit governs the electrical load in order to create the selected load profiles.
- Control and monitoring of the rotary speed of the diesel engine. The control unit communicates with the diesel governor. The rotary speed of the diesel is determined by the current load and the calculated curve of its best efficiency.
- Start and stop of the engine: The control unit stops the engine when no power is need and restarts it.
- Control of the inverter with status check and error handling.

The used diesel engine was a four stroke air cooled engine with one piston. The diesel has a nominal power of 3.5 kW at 3500 rpm and is digitally governed by the unit DG3005.10 of the Company Heinzmann.

The generator is a brushless permanent synchronous generator (manufacturer: Heinzmann) of the nominal electric power of 4.5 kVA at 3500 rpm. It provides

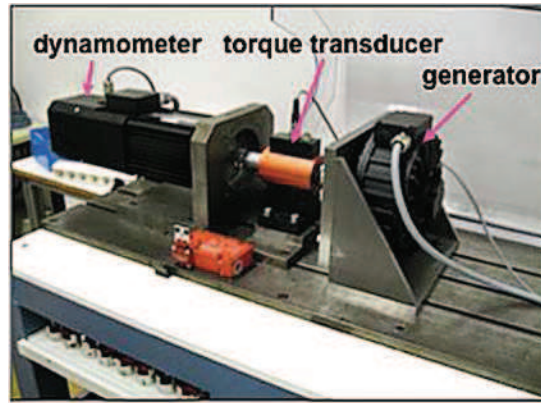


Fig. 3.6-2: Test bench for determination of characteristic maps

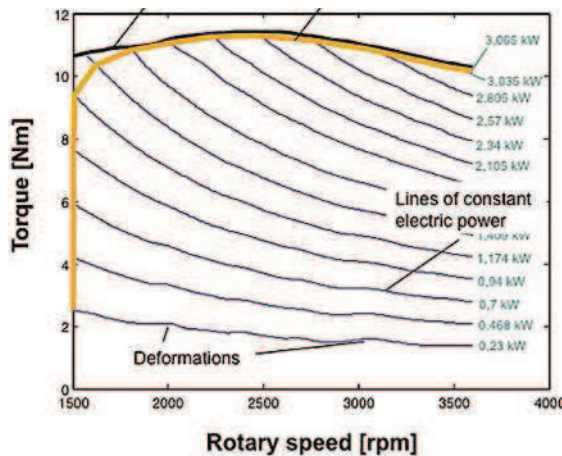


Fig. 3.6-3: Determined characteristic curve of optimum fuel consumption of diesel engine

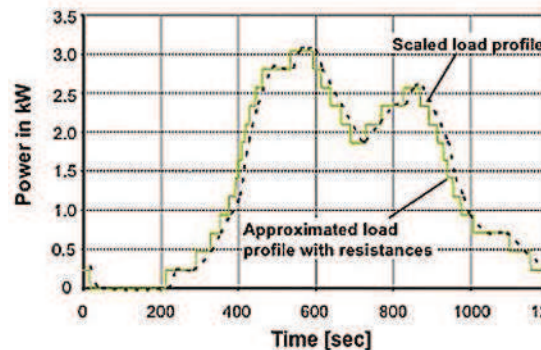


Fig. 3.6-4: Approximation of load profile with resistances

under load a voltage of 150 VAC at 1500 rpm. This was necessary to ensure that the inverter generates a stable voltage of 100 VAC at 50 Hz.

The alternating current was rectified into a direct current at variable voltage. The voltage was transformed by the inverter into a 3-phase alternating current at a constant frequency of 50 Hz. A transformer changed this voltage to 400 VAC (European low voltage grid). The electric load was generated by four parallel resistances which allow 16 different linear increasing levels. The continuous profiles were transformed by the control software into a discrete load profile according to the 16 power levels. The soft-

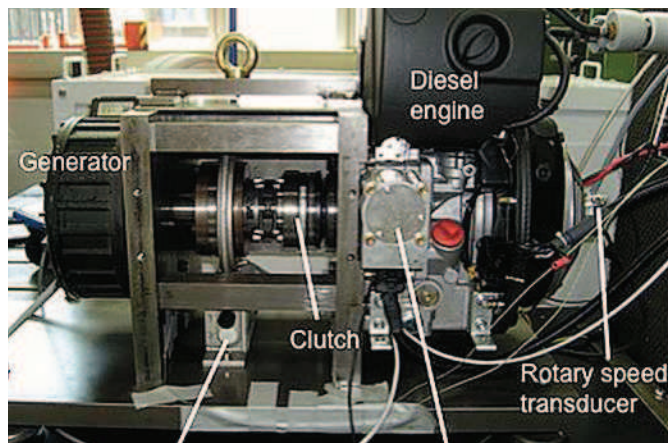
ware switched the resistances in order to approximate the entered load profile (see Figure 3.6-4).

The driving torque and the rotary speed were measured directly at the drivetrain connecting the generator with the diesel engine (Figure 3.6-5).

The test results with the total fuel consumption for the considered load profile with different control strategies are presented in Table 2.

The table shows in normal letters the simulation results, and the experimental results are presented in bold letters. The fuel consumption reduction with the gi-





**Fig. 3.6-5:** Test bench with mounted diesel engine and generation

ven control strategy is indicated in brackets. In all cases, the fuel consumption of the diesel is lower for each profile when operated in VSG mode. The start/stop-function has logically an increasing effect at longer periods of zero power demand. But the rotary speed adaptation has a stronger fuel saving effect than the start/stop function. Furthermore, it

can be seen, that the simulation model predicts very precisely the fuel consumption of the system. The deviation to the measured results is within low percentages.

The simulation model is additionally well suitable for predicting dynamic values like torque and current fuel con-

sumption as shown in Figure 3.6-6 and Figure 3.6-7. In Figure 3.6-7, a peak in fuel consumption can be observed which occurs when the diesel is accelerating to reach the next power level. These peaks are not modelled in the simulation model as it is quasi static.

### Conclusion

The results have shown that operating an APU at variable speed enables a remarkable reduction in fuel consumption of at least 30% for all considered load cycles. This is a very high reduction despite the fact that the tested profiles have a rather low load factor. Certainly, other load profiles with higher load factors (not relevant for APUs) will exhibit a lower but still significant fuel reduction.

The VSG technology provides an economic and ecologic way to provide energy for auxiliaries, particularly for long-haul trucks.

| Control Strategy  | Profile "General businesses" | Profile "Business workdays"        | Profile "Business evening"         | Profile "Farm"                     | Profile "Domestic"                 | Profile "Truck"                    |                                    |
|---|------------------------------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|
| Constant Speed  | <b>E</b>                     | <b>0,272 L</b>                     | <b>0,235 L</b>                     | <b>0,287 L</b>                     | <b>0,266 L</b>                     | <b>0,280 L</b>                     | <b>0,279 L</b>                     |
|   | <b>S</b>                     | <b>0,259 L</b>                     | <b>0,221 L</b>                     | <b>0,271 L</b>                     | <b>0,249 L</b>                     | <b>0,261 L</b>                     | <b>0,260 L</b>                     |
| Constant Speed S/St*  | <b>E</b>                     | <b>0,249 L</b><br><b>(- 8,48%)</b> | <b>0,175 L</b><br><b>(-25,49%)</b> | <b>0,268 L</b><br><b>(-6,77%)</b>  | <b>0,252 L</b><br><b>(-5,49%)</b>  | <b>0,254 L</b><br><b>(-9,04%)</b>  | <b>0,275 L</b><br><b>(-1,26%)</b>  |
|   | <b>S</b>                     | <b>0,237 L</b><br><b>(-8,49%)</b>  | <b>0,162 L</b><br><b>(-26,70%)</b> | <b>0,252 L</b><br><b>(-7,01%)</b>  | <b>0,235 L</b><br><b>(-5,60%)</b>  | <b>0,237 L</b><br><b>(-9,20%)</b>  | <b>0,256 L</b><br><b>(-1,54%)</b>  |
| Variable Speed  | <b>E</b>                     | <b>0,195 L</b><br><b>(-28,46%)</b> | <b>0,154 L</b><br><b>(-34,54%)</b> | <b>0,209 L</b><br><b>(-27,13%)</b> | <b>0,184 L</b><br><b>(31,14%)</b>  | <b>0,198 L</b><br><b>(-29,22%)</b> | <b>0,194 L</b><br><b>(-30,27%)</b> |
|   | <b>S</b>                     | <b>0,185 L</b><br><b>(-28,57%)</b> | <b>0,144 L</b><br><b>(-34,84%)</b> | <b>0,198 L</b><br><b>(-26,94%)</b> | <b>0,171 L</b><br><b>(-31,33%)</b> | <b>0,186 L</b><br><b>(-28,74%)</b> | <b>0,180 L</b><br><b>(-30,77%)</b> |
| Variable Speed S/St*  | <b>E</b>                     | <b>0,189 L</b><br><b>(-30,50%)</b> | <b>0,133 L</b><br><b>(-43,20%)</b> | <b>0,204 L</b><br><b>(-29,03%)</b> | <b>0,179 L</b><br><b>(-32,89%)</b> | <b>0,190 L</b><br><b>(-32,00%)</b> | <b>0,193 L</b><br><b>(-30,81%)</b> |
|   | <b>S</b>                     | <b>0,178 L</b><br><b>(-31,27%)</b> | <b>0,123 L</b><br><b>(-44,34%)</b> | <b>0,192 L</b><br><b>(-29,15%)</b> | <b>0,168 L</b><br><b>(-32,53%)</b> | <b>0,178 L</b><br><b>(-31,80%)</b> | <b>0,179 L</b><br><b>(-31,15%)</b> |
| <b>E = Experiment, S = Simulations; *S/St = control mode with start/stop function</b> |                              |                                    |                                    |                                    |                                    |                                    |                                    |

**Table 2:** Results of total consumption determined by simulations and tests

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## Thank

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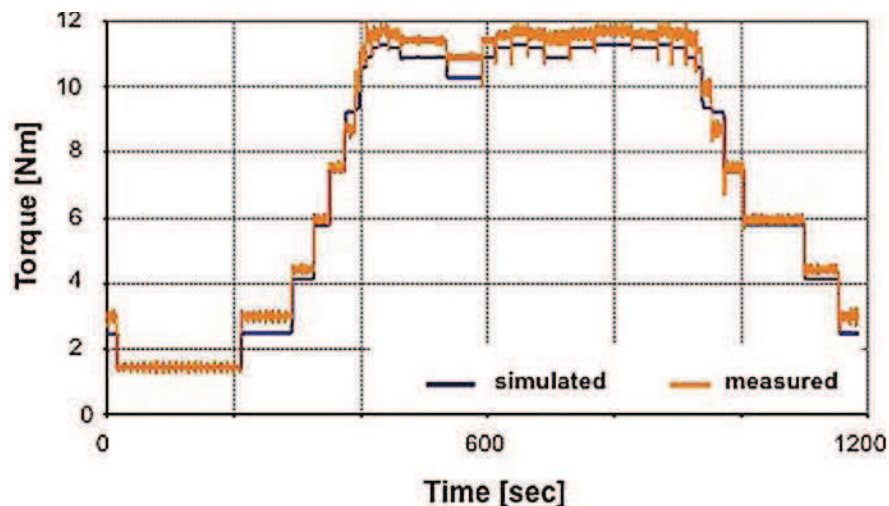


Fig. 3.6-6: Time dependent fuel consumption, simulation and test results

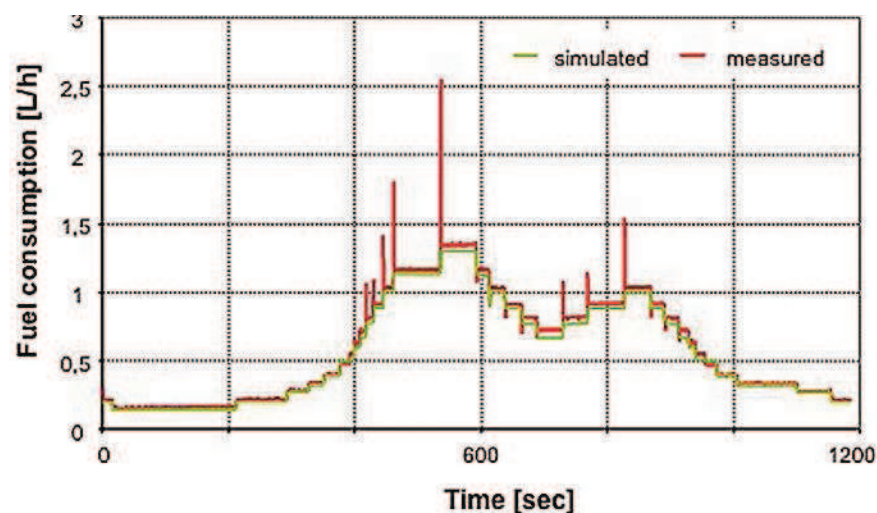


Fig. 3.6-7: Time dependent diesel torque, simulation and test results